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Jet-Induced Emission-Line Nebulosity and Star Formation in the High-Redshift Radio Galaxy 4C41.17

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ABSTRACT

The high redshift radio galaxy 4C41.17 has been shown in earlier work to consist of a powerful radio source in which there is strong evidence for jet-induced star formation along the radio axis. We argue that nuclear photoionization is not responsible for the excitation of the emission line clouds along the axis of the radio source and we therefore construct a jet-cloud interaction model to explain the major features revealed by the detailed radio, optical and spectroscopic data of 4C41.17. The interaction of a high-powered ($\sim 10^{46}$ ergs s^{-1}) jet with a dense cloud in the halo of 4C41.17 produces shock-excited emission-line nebulosity through ~ 1000 km s^{-1} shocks and induces star formation. The C III] to C IV line ratio and the C IV luminosity emanating from the shock, imply that the pre-shock density in the line-emitting cloud is high enough (hydrogen density $\sim 1 - 10$ cm^{-3}) that shock initiated star formation could proceed on a timescale ($\sim$ a few $\times 10^6$ yrs), well within the estimated dynamical age ($\sim 3 \times 10^7$ yrs) of the radio source. The star formation efficiency in the shocked cloud is $\sim 1\%$. Broad (FWHM $\approx 1100 - 1400$ km s^{-1}) emission lines are attributed to the disturbance of the gas cloud by a partial bow–shock and narrow emission lines (FWHM $\approx 500 - 650$ km s^{-1}) (in particular C IV$\lambda\lambda 1548, 50$) arise in precursor emission in relatively low metallicity gas.

The implied baryonic mass $\sim 8 \times 10^{10}\ M_\odot$ of the cloud is high and implies that Milky Way size condensations existed in the environments of forming radio galaxies at a redshift of 3.8. Our interpretation of the data provides a physical basis for the alignment of the radio, emission-line and UV continuum images in some of the highest redshift radio galaxies and the analysis presented here may form a basis for the calculation of densities and cloud masses in other high redshift radio galaxies.

Subject headings: galaxies: active — galaxies: galaxies — elliptical: high-redshift — radio continuum: galaxies

1. Introduction

One of the most intriguing discoveries in the study of high-redshift radio galaxies (HzRG) has been that the rest-frame UV continuum emission from their parent galaxies is aligned with the non-thermal radio emission (McCarthy et al. 1987; Chambers, Miley, & van Breugel 1987). The nature of this continuum and 'alignment effect' has remained unclear. In nearby radio galaxies evidence has been found for jet-induced star formation, scattered light from hidden quasar-like AGN and nebular re-combination continuum (Van Breugel et al. (1985);van Breugel & Dey (1993);Dey et al. (1996);Tadhunter, Dickson, & Shaw (1996);Dickson et al. (1995); di Serego Alighieri et al. (1989);Cimatti et al. (1996)). A good example of radio-aligned UV emission in a very high-redshift radio galaxy is 4C41.17 at $z = 3.800$, which has been extensively studied at optical and radio wavelengths (Chambers, Miley, & van Breugel 1990; Miley et al. 1992; Carilli, Owen, & Harris 1994; Chambers et al. 1996). Recent HST observations have shown that the rest-frame UV morphology of 4C41.17 consists of four main regions, the brightest of which (4C41.17-NE) contains an edge-brightened bifurcated feature consisting of several compact knots located between the radio nucleus and a bright radio knot (Van Breugel et al. 1998).

Deep spectropolarimetric observations with the W. M. Keck Telescope by Dey et al. (1997) show that 4C41.17 is unpolarized between $\lambda_{\rm rest} \sim 1400$ Å $- 2000$ Å, implying that scattered light does not dominate the aligned UV continuum. Instead, the observations show absorption lines and P-Cygni-like features that are similar to those seen in $z \approx 2-3$ star forming galaxies and nearby Wolf-Rayet starburst systems. The possibility of jet-induced star formation in 4C41.17 and other HzRGs has been suggested before (De Young 1981; De Young 1989; Rees 1989; Begelman & Cioffi 1989; Chambers, Miley, & van Breugel 1990; Daly 1990) but until now has lacked sufficient observational basis. In this paper we revisit the jet-induced star formation scenario for 4C41.17 in the light of the new data that are now available, and present a self-consistent model in which interactions between jets and dense clouds in 4C41.17 produce both shock-excited line emission and induce star formation. As we show below, it is fortunate that both phenomena occur since information provided by the former process enables us to better constrain the parameters relating to the latter.

Throughout this paper we assume that H_0=50 km s^{-1} Mpc^{-1} and q_0=0.1. The luminosity distance d_L, angular size distance d_A and linear scale at the redshift of 4C41.17 ($z = 3.800$) are then 51.6 Gpc, 2.24 Gpc, and 10.8 kpc arcsec^{-1} respectively. We follow the notation of Chambers, Miley, & van Breugel (1990) and Carilli, Owen, & Harris (1994) in referring to the radio features (components, knots etc.).

2. HST Observations of 4C41.17 and the Relationship to the Radio Emission

The details of HST imaging of 4C41.17 are given in Van Breugel et al. (1998). Here, we summarize some of the pertinent details of these images and their relationship to the radio

emission in order to facilitate the following theoretical discussion.

The montage in Figure 1 shows three HST images in different bands with the X-band radio images of Carilli, Owen, & Harris (1994) superimposed in the form of contours. The top image is a deep rest-frame UV image (F702W filter, $\lambda_{rest} \sim 1430$Å; 6.0 hours exposure); the middle image was acquired through the F569W filter, which includes Lyα(2.0 hours exposure); the bottom image is a Lyα image (LRF filter at $\lambda_c \sim 5830$ Å; 2.0 hours exposure). All of these images show strongly aligned non-thermal and thermal components. The direct association of the radio components with *both* UV continuum and Lyα emission, together with the spectroscopic evidence for young stars from the Keck observations, strongly points to jet-induced star formation. In particular, the radio knot B2 (the second from the left in these images) is associated with the brightest Lyα region and the F702W and F569W images reveal an interesting bifurcated or oval feature (approximated with a 0.8 by $0.24''$ [$\sim 8.6 \times 2.6$ kpc] oval or parabola, shown enlarged on the right of Figure 1, which we interpret as tracing the locus of newly formed stars. See Van Breugel et al. (1998) for a more detailed discussion of these images.

In Figure 2 a $0.3''$ smoothed version of the F702W image is displayed. This brings out an additional star forming region to the South of the regions evident in the unsmoothed version. Van Breugel et al. (1998) have estimated the star-formation rates in these regions from the UV luminosity, using the relationship between ultraviolet flux and star formation rate determined by Conti, Leitherer, & Vacca (1996). The estimated star formation rates in the various regions are given in table 1.

Following Van Breugel et al. (1998) we adopt the following nomenclature for the components in the HST image: The NE component is the region of edge-brightened UV emission located on the core side of the bright radio knot B2; NEE is the more diffuse component to the East of this. NW is the UV component along the radio axis on the Western side of the radio core and S represents is the clumpy component to the South, revealed by the smoothed image.

The evidence for jet-induced line emission and star formation in the brightest UV emission region in 4C41.17 (4C41.17NE) is compelling and can be summarized as follows (Van Breugel et al. 1998; Dey et al. 1997):

- The star formation rate per square kiloparsec in the four UV bright regions mentioned in the introduction is by far the greatest in 4C41.17NE (Van Breugel et al. 1998). (1996). The morphology of 4C41.17NE and its close proximity to the radio knot, B2, strongly indicate that star formation has been induced by the interaction between the northern jet of the radio source and the cloudy medium of the forming parent galaxy as expected in jet-induced star formation models (e.g. De Young (1989)). The random distribution and lower star formation rates in the 4C41.17S knots, which are comparable to hose of 'Lyman-break' galaxies (Steidel et al. 1996), suggests that star formation here is unaided by bowshocks from the radio jet.

- The HST Lyα image shows a bright arc-shaped feature near B2 at the apex of the

edge-brightened UV structure, suggestive of a strong shock at a location where the jet interacts with dense ambient gas. Such emission-line features near bright radio structures are also often seen in nearby radio galaxies (van Breugel et al. 1985; Tadhunter et al. 1994) and these have a similar interpretation.

- The kinematics of the Lyα emission is very much disturbed in the aligned component with velocities with respect to systematic $\sim 500 - 1400\,\mathrm{km\,s^{-1}}$ and velocity dispersions $\sigma \sim 300 - 600\,\mathrm{km\,s^{-1}}$ (Dey et al. 1997; Chambers, Miley, & van Breugel 1990), suggesting large (projected) velocities and strong turbulence caused by jet/cloud interactions.

  It follows from the above three points that the emission lines from this galaxy are probably related either to the star-forming region or to emission from radiative cloud shocks rather than excitation by UV-X-ray emission from the active nucleus.

- The Keck spectra by Dey et al. (1997) show that emission-line gas associated with the components B1, B2 and B3 of the inner radio source 4C41.17 consists of two distinct kinematic components: relatively narrow lines for all species (Lyα, N V, Si II, Si IV, C IV, He II, and C III) with FWHM $\approx 500 - 650\,\mathrm{km\,s^{-1}}$ ($\sigma \approx 220 - 270\,\mathrm{km\,s^{-1}}$), and broad Ly$\alpha$ and C III] with FWHM $\approx 1100 - 1400\,\mathrm{km\,s^{-1}}$ ($\sigma \approx 470 - 600\,\mathrm{km\,s^{-1}}$). (Si IV is possibly broad also; however the estimate of the line width is complicated by associated absorption.) We assume that the narrow velocity components are related to the jet-driven radiative shocks, and the broad components by filaments pulled out of the cloud through the action of the Kelvin-Helmholtz instability at the jet-cloud interface. This is discussed further in § 3.

- The brightest Lyα emission is found on the same side (East) which has the outer hotspot of 4C41.17 closest the nucleus. This agrees with the general radio / EELR morphological asymmetry correlation seen in powerful FR-II radio galaxies (McCarthy, van Breugel, & Kapahi 1991), and suggests that the radio source has been impeded in this direction as a result of its encounter with relatively dense gas.

- As we noted in the introduction, the absence of any evidence for a polarized, scattered AGN continuum supports the notion that, in the case of 4C41.17, the active nucleus is not responsible for the extended UV emission.

3. Interaction of Clouds in the Lyα Halo with the Radio Jets

4C41.17 is located at the center of a large Lyα halo (Chambers, Miley, & van Breugel 1990). The passage of relativistic jets through such a halo will inevitably result in substantial jet–cloud interactions. In the case of the jet-cloud interaction evident near the radio knot B2 we suggest that a glancing incidence of the jet on the cloud causes a partial bow-shock to be driven in to the cloud. This is manifest through the associated shock-excited line emission and associated star formation in the bifurcated structure referred to above. The jet deposits much of its momentum

at this site and it continues onward to the knot B3 where the decelerated jet plasma accumulates as a radio "lobe". In this section we estimate physical cloud and jet parameters implied by this interaction model and then consider other emission regions in the HST images.

An important feature of the spectroscopic observations of 4C41.17 is the three kinematically distinct components namely the broad emission lines ($\sigma \sim 470 - 600\,\mathrm{km\,s^{-1}}$), the narrow emission lines ($\sigma \sim 220 - 270\,\mathrm{km\,s^{-1}}$) and the narrow absorption lines ($\sigma \sim 170 - 340\,\mathrm{km\,s^{-1}}$). We suggest that these components arise in the following way (see Figure 4). The narrow emission lines have a velocity dispersion similar to the halo and are formed either by locally induced photoionization of halo gas or in the winds of newly formed stars. The natural location for the narrow absorption lines is in the atmospheres of the young stars and in some cases the narrow absorption and emission lines comprise a typical P-cygni-like profile characteristic of winds from young stars see Dey et al. (1997). We suggest that the broad emission lines arise from shock-excited gas which has been significantly disturbed by the jet-cloud bow shock. This phenomenon is also observed in low redshift radio galaxies (van Breugel et al. 1985; Tadhunter 1991).

Many of the observed narrow emission lines could be produced either in the shock or in the photoionized winds of the newly formed stars. An important exception is C IV which is weak in stars older than 3×10^6 yrs (Leitherer, Robert, & Heckman 1995). Moreover, when this line *is* present in emission in young stars, its strength is comparable to the absorption strength. In 4C41.17 the C IV emission line strength dwarfs the absorption component and we therefore completely attribute this component of emission to the effects of the radiative cloud shock. The C IVemission is narrow and this is a strong indication that most of the flux from this line originates in the precursor material ahead of the cloud bow shock. As we show below this is consistent with the velocity $\sim 1000\,\mathrm{km\,s^{-1}}$ that we adopt for the normal component of this shock.

3.1. The Jet Bow Shock

Let us now focus on the brightest emission line knot adjacent to knot B2 in the radio image. If a large fraction of the jet momentum flux, F_p is absorbed at this interaction site, and the cross-sectional area of the (presumably jittering) jet over which the momentum is spread is A_jet, then the velocity of the bow shock driven into the cloud of density ρ_cl is given by $v_\mathrm{sh} \approx (F_\mathrm{p}/\rho_\mathrm{cl} A_\mathrm{jet})^{1/2}$. For a relativistic jet, the energy flux, $F_\mathrm{E} = cF_\mathrm{p}$; for a non relativistic jet, $F_\mathrm{E} \approx v_\mathrm{jet}/2F_\mathrm{p}$. The FWHM of knot B2 $\approx 0.11''$ (Chambers, Miley, & van Breugel 1990) and this angular scale provides an upper limit for $A_\mathrm{jet} \approx 1.1 \times 10^{43}\,\mathrm{cm}^2$ since the radio emission resulting from the jet burrowing into the cloud emanates from a larger volume than just the head of the locally produced radio cocoon. We therefore obtain the corresponding lower limits for the bow shock velocity:

$$\begin{aligned} v_\mathrm{sh} &\gtrsim 1100\, F_\mathrm{E,46}^{1/2}\, n_\mathrm{H}^{-1/2} && \mathrm{km\,s^{-1}} \quad \text{(relativistic)} \\ v_\mathrm{sh} &\gtrsim 1600\, F_\mathrm{E,46}^{1/2} \beta_\mathrm{jet}^{-1/2}\, n_\mathrm{H}^{-1/2} && \mathrm{km\,s^{-1}} \quad \text{(non-relativistic)} \end{aligned} \qquad (3\text{-}1)$$

where $10^{46}\,F_{\rm E,46}$ ergs s^{-1} is the jet energy flux and $n_{\rm H}$ cm^{-3} is the Hydrogen density in the cloud. These velocity limits are to be compared to the velocity with respect to systemic $\sim 500 - 1400\,{\rm km\,s^{-1}}$ of Lyα in this region and also the FWHM of Ly$\alpha \sim 700 - 1400\,{\rm km\,s^{-1}}$. With radiative shocks, comparable fluxes of Lyα are emitted from both precursor and shocked regions so that these two measures of the Lyα velocity field give us a good indication that the normal component of the bow-shock velocity is of order $1000\,{\rm km\,s^{-1}}$.

3.2. Shock-excited line emission

Let us now consider the emission line fluxes and how these relate to the ambient density and shock velocities. In so doing we are utlising data with quite different spatial resolutions, the Keck spectra and the HST line and continuum images. The emission line components revealed by the Keck spectra are not resolved by the Keck spectra and we would expect contributions to the emission line luminosity from a number of the Lyα emitting regions. However, we expect the most significant contribution to come from the brightest Lyα emitting region in the immediate vicinity of the radio knot B2. Moreoever, the stellar features in the Keck spectra orginate from young stars and the site of these is revealed by the HST UV continuum images. Therefore, there is good reason to believe that the Keck spectra relate to the jet-cloud interaction near radio component B2.

The strongest emission lines in the spectrum are Lyα and C IV$\lambda\lambda1548, 50$. As is well known, the transfer of Lyα is subject to strong resonant scattering effects making it difficult to directly infer shock parameters from emission line fluxes. C IV is not as strongly affected by resonant scattering, and we therefore use the luminosity of the C IV doublet to constrain shock parameters. As we have shown above, the favored velocity of the normal component of the bow shock velocity is in the vicinity of $1000\,{\rm km\,s^{-1}}$ and it is useful to note that is that this is compatible with a number of features of the emission. First, the C IV emission from a shock with this velocity is dominated by the precursor and the velocity dispersion of C IV ($\sim 250\,{\rm km\,s^{-1}}$ is in the range of halo velocity dispersions is consistent with precursor dominated emission. Second, the HST Lyα image shows Lyα emission ahead of the presumed location of bow-shock (knot B2) indicating significant precursor emission in Lyα.

The emission from shocks with velocities $\leq 500\,{\rm km\,s^{-1}}$ were calculated for solar metallicities by Dopita & Sutherland (1996a) and Dopita & Sutherland (1996b). Recent work (Sutherland, Allen, & Kewley 1999) extends these calculations to higher velocities ($\sim 800 - 900\,{\rm km\,s^{-1}}$) and lower metallicities. Extension to even higher velocities $\gtrsim 1000\,{\rm km\,s^{-1}}$ is difficult at present. However, the results from the Sutherland et al. (1999) calculations certainly give one an indication of the magnitude of shock emission and the trend with increasing velocity.

For a shock of area $A_{\rm sh}$, proceeding into gas with pre-shock Hydrogen density, $n_{\rm H}$ we represent

the shock luminosity in C IV, L(C IV), in the form

$$L(\text{C IV}) = \alpha(\text{C IV})\, n_{\rm H}\, A_{\rm sh} \tag{3-2}$$

The shock coefficient α(C IV) is shown as a function of shock velocity and metallicity in Figure 3. The earlier Dopita and Sutherland solar shock grid produces C IV emission with a coefficient α(C IV) ranging between 6×10^{-5} and 5×10^{-4}, with the dominant source of C IV emission coming from the shock structure itself. Extrapolation to $1000\,\text{km s}^{-1}$ would give α(C IV) just over 1×10^{-3}. The extended grid of (Sutherland, Allen, & Kewley 1999) for higher velocities and lower metallicities shows that C IV emission is much more efficient than extrapolated from the earlier low velocity grid, as C IV emission from the precursor region comes to dominate. At low metallicities the C IV emission in further enhanced, as the temperature of the precursor increases and C IV$\lambda\lambda1548, 50$ is excited more efficiently. For abundances found in the Magellanic Clouds (LMC & SMC,Russell (1989)), the α(C IV) coefficient grows rapidly to values around 0.01. Solar and SMC abundances also rise to similar values and it is not until [Fe/H] falls to -2.0 or lower that the efficiency finally falls below this.

Therefore, for shock velocities $\gtrsim 600\,\text{km s}^{-1}$ and for a range of metallicities, particularly LMC metallicities, α(C IV) ~ 0.01 so that we adopt this as a fiducial value. Also, as we have noted above, the shock emission in this case is dominated by the emission from the precursor as distinct from the low velocity case where the emission is dominated by the shocked gas. This feature of shock-induced emission is consistent with the observed velocity dispersion. The other important point to note is that because of the timescales involved ($\sim 10^7$ yr), shocks with the velocities which are relevant here, are fully radiative. For the the velocity range of $700 - 900\,\text{km s}^{-1}$ at LMC abundances, the cooling timescales are $(9.4 - 16.3) \times 10^5 (1.0/n_{\rm H})$yrs, so that the shocks are fully radiative on timescales short compared to the source timescale for densities $\gtrsim 1.0\,\text{cm}^{-3}$.

As a fiducial value for the shock area we take the projected area, $A_{\rm p} \approx 35\,\text{kpc}^2$, obtained by counting HST pixels in the F569W image in the NE region, above a 'sky' value, it is about 50% more than the area of the oval area the F702W and F569W images in Figure 1 and is equivalent to the dashed rectangle in the centre right panel. With this fiducial value for $A_{\rm sh}$ the predicted C IV luminosity from the shock is

$$L(\text{C IV}) \approx 3 \times 10^{42} \left(\frac{\alpha(\text{C IV})}{0.01}\right) n_{\rm H} \left(\frac{A_{\rm sh}}{A_{\rm p}}\right)^{-1} \text{ergs s}^{-1} \tag{3-3}$$

where the value of α(C IV) is really an average of the different normal components of velocity over the bow-shock surface. Comparing the predicted C IV luminosity with that observed, $\approx 4.2 \times 10^{43}\,\text{ergs s}^{-1}$, one can see that, if a fraction f(C IV) the C IV luminosity emanates from this region, then $n_{\rm H} \sim 10 f(\text{C IV})\,\text{cm}^{-3}$.

By way of the lower limits for the bow shock velocity [see equations(3-1)] upper limits on the

energy flux can be estimated from:

$$\begin{aligned} F_{\mathrm{E},46} &\lesssim 0.77\, n_{\mathrm{H}} \left(\frac{v_{\mathrm{sh}}}{10^3\ \mathrm{km\,s^{-1}}}\right)^2 \mathrm{ergs\,s^{-1}} && \text{(relativistic)} \\ F_{\mathrm{E},46} &\lesssim 0.39\, n_{\mathrm{H}}\, \beta_{\mathrm{jet}} \left(\frac{v_{\mathrm{sh}}}{10^3\ \mathrm{km\,s^{-1}}}\right)^2 \mathrm{ergs\,s^{-1}} && \text{(non-relativistic)} \end{aligned} \tag{3-4}$$

Taking into account the likely range of number densities and the range of velocities in the shocked material, it is evident that the upper limit on the jet energy flux is of order 10^{47} ergs s^{-1} for a relativistic jet. For $\beta_{\mathrm{jet}} \approx 0.1$, the upper limit is of order 10^{46} ergs s^{-1}. However, note that a jet with $\beta_{\mathrm{jet}} \sim 0.1$ is unlikely to be supersonic. We expect that all jets in such sources are initially relativistic and the critical velocity at which they become subsonic is approximately $0.3\,c$ (Bicknell 1994).

3.3. Star formation in the shocked cloud

Star formation initiated by shocks has been a process that has been considered in many contexts for some time and much of the theoretical underpinnings of the subject were treated in a fundamental paper by Elmegreen & Elmegreen (1978). They consider a shocked layer of surface density σ confined by both self gravity and an external pressure P_{ext}. The reader is referred to Figure 5 for a description of the shock geometry. The Elmegreen and Elmegreen analysis involves the parameter

$$A = \left[1 + \frac{2P_{\mathrm{ext}}}{\pi G \sigma^2}\right]^{-1/2} \tag{3-5}$$

where G is the constant of gravitation. Such a layer is strongly self-gravitating when $A \to 1$; the confinement is dominated by external pressure when $A \to 0$. With ρ_{00} as the density at the layer midplane, and H as the half-thickness of the layer, the temporal frequency ω and the wavelength, λ, of a perturbation are given in terms of their non-dimensional values, Ω and ν, by

$$\omega = (4\pi G \rho_{00})^{1/2}\, \Omega \qquad \text{and} \qquad \lambda = 2\pi H \nu^{-1} \tag{3-6}$$

In order that jet-induced star formation be effective, the time-scale for gravitational instability should be less than (and preferably much less than) the dynamical time-scale $\sim 10^7$ yr for the shocked region that we are considering. We therefore adopt a fiducial timescale of 10^6 yr for gravitational instability. The external pressure confining the recombination layer following a strong radiative shock into material with a pre-shock density ρ, is $P_{\mathrm{ext}} \approx \rho v_{\mathrm{sh}}^2$ and the surface density of the accreting layer is $\sigma = \rho v_{\mathrm{sh}} t$. Hence, the instability parameter defined by equation (3-5) above is given by

$$A = \left[1 + 4.0 \times 10^3 n_H^{-1} t_6^{-2}\right]^{-1/2} \approx 1.6 \times 10^{-2}\, n_{\mathrm{H}}^{1/2} t_6 \tag{3-7}$$

This places the layer in the regime where it is not dominated by self-gravity. Interestingly, however, fragmentation on a short enough timescale can occur. This is revealed by the following estimates of the instability timescale, the length scale corresponding to the maximal growth rate

and the minimal length scale on which instability will occur. Fragmentation in this parameter regime has also been pointed out by Whitworth et al. (1997).

For $A << 1$, Elmegreen & Elmegreen (1978) numerically estimate the nondimensional values of the maximal growth rate, $\Omega_{\rm mgr}$, the wave number for maximal growth, $\nu_{\rm mgr}$, and the maximum wave number for instability, ν_c:

$$-\,\Omega^2_{\rm mgr} \doteq 0.139 \qquad A\nu_{\rm mgr} \doteq 0.294 \qquad A\nu_c \doteq 0.639 \tag{3-8}$$

These non-dimensional values can be converted to physical units using the above relations between the half-thickness of the layer, the surface density and the central density, $HA = 2^{-1}\sigma\rho_{00}^{-1}$, resulting in the following expressions for the timescale of maximum growth, $t_{\rm mgr}$, the wavelength, $\lambda_{\rm mgr}$ of the maximally growing perturbation and the minimum wavelength for instability, $\lambda_{\rm min}$:

$$t_{\rm mgr} \doteq 58 \left(\frac{\rho}{\rho_{00}}\right)^{1/2} n_{\rm H}^{-1/2}\,{\rm Myr} \tag{3-9}$$

$$\lambda_{\rm mgr} \doteq 11 \left(\frac{\rho}{\rho_{00}}\right) \left(\frac{v_{\rm sh}}{10^3\ {\rm km\ s^{-1}}}\right) t_6\ {\rm kpc} \tag{3-10}$$

$$\lambda_{\rm min} \doteq 5.1 \left(\frac{\rho}{\rho_{00}}\right) \left(\frac{v_{\rm sh}}{10^3\ {\rm km\ s^{-1}}}\right) t_6\ {\rm kpc} \tag{3-11}$$

The relevance of these estimates to the present situation is realized when we allow for the fact that in a radiative shock the ratio, ρ_{00}/ρ, of recombination to pre-shock densities is typically of order 100. For $\rho_{00}/\rho \sim 100$, $t_{\rm mgr} \approx 6-2\,{\rm Myr}$ for $n_{\rm H} = 1-10\,{\rm cm}^{-3}$. The linear scale corresponding to the maximum growth rate and the minimum growth scale both increase with time and indicate that the sizes of the star formation regions are of order a few hundred parsecs after about 3×10^6 yr.

Thus, for the range of pre-shock densities, $n_{\rm H} \sim 1-10\,{\rm cm}^{-3}$ that we have identified from the shock dynamics, it is quite clear that gravitational instability occurs on timescales comfortably within the dynamical timescale of the jet-cloud interaction. Moreover, the sizes of the star formation regions fit well within the structures observed at the interaction site. Indeed, it is interesting to note the existence of knots in the star formation region on a scale of 2-3 HST pixels corresponding to a spatial scale of $1-1.5$ kpc.

3.4. The disruptive effect of the jet-cloud interaction

It is well known (e.g. Klein, McKee, & Colella (1994) and references therein) that shocks can disrupt clouds on timescales of the order of a shock crossing timescale, $t_{\rm sh} \sim 9.7 \times 10^5\,(L/{\rm kpc})(v_{\rm sh}/10^3\ {\rm km\ s^{-1}})^{-1}$ yrs where L is the relevant scale-size. For the transverse size of 3.4 kpc ($L = 1.7$kpc) this would be of the order of 1.6×10^6yrs if the transverse velocity is as high as $1000\,{\rm km\,s^{-1}}$. However, the transverse component of the bow-shock velocity is less than the velocity of advance of the bow shock and the shock-shredding timescale is likely to be at least a factor of two higher than this estimate. In this case the shock shredding timescale

would be comparable to or higher than the star formation timescale, especially for a cloud density $\sim 10\,cm^{-3}$. Another way of looking at this is that on the radio source timescale $\sim 10^7$ yrs, the bow shock should propagate to the edge of the cloud. When that happens one does not expect much of that region of the cloud to survive. From the HST images in Figure 1, this appears to be the case. The emission-line and enhanced star-formation activity is confined to the arc-shaped region near B2.

3.5. Relation to the dynamics of the radio source

An important consistency check on any model for a radio source relates to the radio luminosity and jet energy flux. In principle, one can use estimates of the jet energy flux obtained from the monochromatic power, P_ν of a lobe and an estimate of the ratio κ_ν of monochromatic power to jet energy flux (Bicknell, Dopita, & O'Dea 1996; Bicknell et al. 1998). These estimates depend upon the age of the source and the estimate of the magnetic field in the lobe. The application of this method to high redshift radio galaxies meets with some complications resulting from the fact that the theory applies to the "low frequency" region of the spectrum defined to be that region for which the frequency is less than the radiative break frequency. Moreover the estimation of the minimum energy magnetic field also depends upon measurements from the low frequency region which, generally for high redshift radio galaxies, is inaccessible. We therefore adopt the following approach: The estimate of κ_ν and the estimate of the minimum energy magnetic field are both equally valid if applied to the *extrapolated* low frequency spectrum. At frequencies greater than the break frequency, both the measured flux density and power of a particular component at frequencies ~ 1 GHz are underestimates of the extrapolated quantities. If a spectrum breaks at a frequency ν_b with a change in spectral index of $\Delta\alpha$, then the ratio of extrapolated to measured flux densities is $(\nu/\nu_b)^{\Delta\alpha}$. If, as in the standard injection plus cooling model, $\Delta\alpha = 0.5$, then a ratio of extrapolated to measure flux densities ~ 10 implies a break frequency in the observer's frame $\sim 10\,$MHz and a corresponding break frequency in the rest frame $\sim 50\,MHz$. It is therefore unlikely that the ratio of extrapolated to measured flux densities is greater then 10.

What do we take to be the "lobe" in 4C41.17? Chambers et al. (1990) have argued that this should be component B3 rather than component C, which has a very steep spectral index and does not appear to be connected to the inner components. Component C is possibly a relic of earlier activity in this galaxy and we adopt the Chambers et al. (1990) interpretation of component B3 as the lobe. The $1.5 - 4.7$ GHz spectral index of B3 is 1.2 (Carilli, Owen, & Harris 1994), consistent with a typical low frequency spectral index of 0.7 and a cooling induced break of $\Delta\alpha \approx 0.5$. Therefore the above remarks on the extrapolated flux density are pertinent.

The monochromatic luminosity of B3 at rest frequency $\nu_{\rm rest} = (1+z)\nu_{\rm obs}$ is given by

$$P_{\nu_{\rm rest}} = \frac{4\pi D_{\rm L}^2}{1+z}\, F_{\nu_{\rm obs}} \tag{3-12}$$

where $D_{\rm L} = 5.16 \times 10^4$ Mpc is the luminosity distance and $F_{1.465\,{\rm GHz}} = 85\,{\rm mJy}$ (Carilli, Owen, & Harris 1994). Thus, $P_{7.0} \approx 5.7 \times 10^{34}\ {\rm ergs\,s^{-1}\ Hz^{-1}}$.

We estimate the ratio of monochromatic luminosity to jet power using

$$\kappa_\nu \approx (a-2)\, C_{\rm syn}(a)\, (\gamma_0 m_{\rm e} c^2)^{(a-2)} \left[1 - (\gamma_1/\gamma_0)^{-(a-2)}\right]^{-1} \; B^{(a+1)/2} \nu^{-(a-1)/2}\, \tau \tag{3-13}$$

In this equation a is the electron spectral index ($N(E) \propto E^{-a}$), γ_0 and γ_1 are the upper and lower cutoffs in the Lorentz factor of the electron distribution, B is the magnetic field, $C_{\rm syn}(a) = 4\pi c_5(a) c_9(a) (2c_1)^{(a-1)/2}$ incorporates a number of Pacholczyk (1970) synchrotron parameters and $\tau = f_{\rm e} f_{\rm ad} t$ is an evolutionary parameter which depends on $f_{\rm e} \approx 1$ the electron/positron fraction of the internal energy, an adiabatic factor $f_{\rm ad} \sim 0.5$ and the age of the lobe. In order to obtain theoretical estimates of $\kappa_{7.0}$ we estimate the minimum energy magnetic field from the peak surface brightness of knot B3 in the 1.465 GHz image (Carilli, Owen, & Harris 1994) and a FWHM of $0.11''$ (Chambers et al. 1990). Since there are a number of uncertain parameters, we bracket the estimates by values of extrapolated flux densities and powers between 1 and 10 times the measured values and values of $\tau = 10$Myr. (Chambers et al. (1990) estimated the dynamical lifetime of B3 to be approximately 3×10^7 yr corresponding to $\tau \approx 15$ Myr.) The other important parameter in these calculations is the ratio of the actual value of the magnetic field to the minimum energy value. This is probably the most important parameter for reconciliation of the radio power and the jet energy flux, since $\kappa_\nu \propto B^{1+\alpha}$. For Cygnus A, Carilli et al. (1991) estimated that the magnetic field strength is about 0.3 times the minimum energy value in order to reconcile the lobe advance speed estimated from spectral aging with that estimated from ram pressure balance. Likewise, Wellman, Daly, & Wan (1997b) and Wellman, Daly, & Wan (1997a), using the same argument, estimated that $B \approx 0.25 B_{\rm min}$ from a sample of powerful radio galaxies. Therefore, in table 2, the results of the calculations for $\kappa_{7.0}$ and the resultant estimates of the energy flux, $F_{\rm E} = \kappa_{7.0}^{-1} P_{7.0}$ are given for different extrapolated flux densities, a value of $\tau = 10$Myr and for $B = B_{\rm in}$ and $B = 0.25 B_{\rm min}$. As one can see from the table, the radio power is consistent with a jet energy flux $\sim 10^{46}\ {\rm ergs\,s^{-1}}$ for $F_{\nu,{\rm extrap}}/F_\nu \gtrsim 10^{0.5}$ and $B/B_{\rm min} = 0.25$ and this is consistent with the upper limits on the jet energy flux given by equations 3-4.

3.6. Cloud mass and gravitational instability of clouds in the halo of 4C41.17

In order to estimate the cloud mass involved in this interaction, we assume that the cloud is as deep as it is wide (3.4 kpc) and we assume an area equal to the extent of the entire Lyα-bright region adjacent to B2 ($\approx 65\ {\rm kpc}^2$). This yields a mass $\approx 8 \times 10^{10} f({\rm C\ IV}) M_\odot$. The cloud mass inferred for the cloud interacting with the jet is well in excess of the Jeans mass. Presumably this cloud is not exceptional as far as clouds in the halo of 4C41.17 are concerned. Indeed, the existence of other regions forming stars, albeit at a lower rate (see table t:sfr and Van Breugel et al. (1998)), indicates that star formation is also occurring within this galaxy as a result of other more standard processes ensuing from gravitational collapse. The freefall time for a cloud

of density ρ is $t_{\rm ff} \approx 2100\, \rho^{-1/2} \approx 1.4 \times 10^7\ \left(n_{\rm H}/10\,{\rm cm}^{-3}\right)^{-1/2}$ yr – comparable to the dynamical timescale of the radio source itself.

3.7. Other regions of Lyα flux

For a *uniform* density of $n_{\rm H} = 1.0{\rm cm}^{-3}$, the extent of the ionized precursor zone for a $700 - 900\,{\rm km\,s}^{-1}$ shock at LMC metallicity ranges from $4.2 - 9.4\,{\rm kpc}$ (Sutherland, Allen & Kewley 1999). The extent of the precursor emission is inversely proportional to density. Hence, the Lyα emitting region, approximately 4 kpc in extent to the east of B3 could be shock precursor emission from a region of density $\sim 1.1 - 2.4\,{\rm cm}^{-3}$. Similarly the other Ly$\alpha$ emitting region, $\sim 10\,{\rm kpc}$ in extent on the western side of the galaxy and beginning at another radio knot could be precursor emission associated with the expansion of that radio component if the density is approximately $0.4 - 0.9\,{\rm cm}^{-3}$. Thus, both of these regions could be the result of jet interactions in slightly more tenuous regions.

4. Conclusions

We have shown that the recent observational evidence for jet-induced star formation in 4C41.17 can be understood through a model in which clouds with a density ($n_{\rm H} \sim 1 - 10\,{\rm cm}^{-3}$) in the galaxy are compressed by the bow shock resulting from interaction with the jet. Using the C IV emission to estimate the density leads to a consistent scenario for shock induced star formation. The gravitational timescales estimated from the density are well within the dynamical timescale of the radio source and suggest that, compared to the radio source timescale, star formation should occur almost instantaneously. Some of the important features of the observations which lead to a reasonably self-consistent model include the large velocities with respect to systemic and large velocity dispersions of the Lyα emitting region near B2. These imply relatively large bow-shock velocity $\sim 1000{\rm km s}^{-1}$ and an upper limit on the jet energy flux $\sim 8 \times 10^{46}{\rm ergs s}^{-1}$. These estimates are consistent with the radio source energy budget if the size of the momentum deposition region is smaller than the upper limit $\sim 0.11''$ and/or if the magnetic field is approximately 0.25 times the equipartition value. Our analysis therefore supports the general picture of jet-induced star formation in the papers cited in the introduction.

In view of the wealth of data on 4C41.17 and the physics revealed by the combined HST and VLA observations, it is clear that jet-induced star formation can indeed be a significant process in many very high-redshift radio galaxies. Theoretically this was anticipated 10 years ago, on the basis of the dense, cloudy media expected in forming galaxies and the presence of extremely luminous (10 - 100 times the luminosity of Cygnus A) radio sources embedded in them. Observationally, at present, 4C41.17 is unique in that direct evidence for jet-induced star formation exists. However, the radio/UV alignments seen in many $z > 3$ radio galaxies, together

with their blue colors and the very similar rest-frame optical and radio source sizes (Van Breugel et al. 1998)strongly suggest that jet-induced star bursts may occur in most high-redshift radio galaxies.

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Tables

Component	Diameter (kpc)	SFR ($M_\odot$ y^{-1})
NW	11	60
NE	11	200
NEE	11	30
S	22	110

Table 1: Star formation rates in the different UV components, estimated by Van Breugel et al. (1998).

$F_\nu^{\rm extrap}/F_\nu^{\rm obs}$	$P_{7.0\rm GHz}$ ergs s^{-1} Hz^{-1}	$B_{\rm min}$ (Gauss)	$B/B_{\rm min}$	$\kappa_{7.0}$ (Hz^{-1})	$F_{\rm E}$ (ergs s^{-1})
1	5.7×10^{34}	3×10^{-4}	1	1×10^{-10}	6×10^{44}
			0.25	9.5×10^{-12}	6×10^{45}
$10^{1/2}$	1.8×10^{35}	3.5×10^{-4}	1	2×10^{-10}	1×10^{45}
			0.25	2×10^{-11}	1×10^{46}
10	5.7×10^{35}	5×10^{-4}	1	3×10^{-10}	2×10^{45}
			0.25	3×10^{-11}	2×10^{46}

Table 2: Estimates of the jet energy flux from the radio power of component B3.

Figure Captions

Figure 1 Montage of three HST images taken through the F702W, F569W and Lyα filters. The X-band radio images of Carilli, Owen, & Harris (1994) are superimposed in the form of contours.

Figure 2 The F702W HST image smoothed to $0.2''$ resolution. This enhances the star-forming region to the South.

Figure 3 Radiative shock models from (Sutherland, Allen, & Kewley 1999) for a range of metallicities. The shaded bar indicates the range of α(C IV) for shock velocities over $600\,\mathrm{km\,s^{-1}}$ The curves are labeled with the metallicities of each series. The straight line labeled DS95 is a least squares fit to the results of the $150-500\,\mathrm{km\,s^{-1}}$ grid of solar metallicity models from Dopita & Sutherland (1996a) and Dopita & Sutherland (1996b). The earlier grid does not extrapolate well to the higher velocity range of $500-900\,\mathrm{km\,s^{-1}}$, where the C IV emission from the precursor rapidly rises producing the higher than expected α(C IV) values. Lower metallicity models with SMC and LMC abundances are very efficient C IV producers due to hotter precursors in those models.

Figure 4: The suggested morphology of a jet-cloud interaction as it relates to 4C41.17. The deflection of the jet at the cloud is mediated by a shock which is responsible for the knot of radio emission. The high pressure drives a radiative shock into the cloud and this initiates star formation. Some of the narrow emission lines ($\sigma \approx 220-270\,\mathrm{km\,s^{-1}}$) characteristically associated with star formation originate from this region. Other narrow emission lines, in particular C IV$\lambda\lambda1548,50$, originate from the shock-excited line emission from behind the radiative cloud shock. The low Mach number flow behind the jet shock causes dense filaments of gas to be drawn out of the cloud via the Kelvin-Helmholtz instability. This is the origin of the broader ($\sigma \approx 470-600\,\mathrm{km\,s^{-1}}$) emission lines.

Figure 5: Illustration of a radiative shock and the associated post-shock radiatively cooled layer wherein star formation is envisaged to occur. As the shock progresses through the pre-shock gas (density ρ) the column density of the cool layer accumulates rendering it more and more gravitationally unstable.

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